Astrophysics Branch (SSA) Overview

Scientists in the Astrophysics Branch pursue a wide range of laboratory and observational astronomy research. The Branch is particularly interested in studying the physical and chemical properties of astronomical phenomena by observing their radiation at infrared (and ultraviolet) wavelengths, beyond the range of visible light.

Planets, stars, and the interstellar medium of the Milky Way and other galaxies are rich in infrared spectral features which provide clues to their origins, physics, chemistry, and evolution. SSA researchers use state-of-the-art laboratories, ground-based, airborne, and space-based observatories to conduct their research. Astrophysics Branch scientists, engineers, and technicians also play key roles in developing new NASA space and airborne missions and instruments such as SIRTF, NGST, and SOFIA. The primary products of the Astrophysics Branch are new observations of the universe and new instrumentation developed to make these observations.

Thomas P. Greene
Chief, Astrophysics Branch (SSA)

THE NEARBY STARS (NSTARS) PROJECT

D.E. Backman

NStars is a project based at Ames to produce a comprehensive Web-accessible Database on stars closer than 80 light years to Earth and to promote further observations of those stars by the astronomical community. This effort supports present and future NASA Origins missions such as the Space Infrared Telescope Facility (SIRTF), Stratospheric Observatory for Infrared Astronomy (SOFIA), and the Terrestrial Planet Finder (TPF). For example, TPF is planned as an array of infrared space telescopes capable of detecting Earth-like planets orbiting our nearest neighbor stars. This is such a technically difficult task that TPF will not be able to survey all stars within its distance range during a reasonable mission lifetime. NStars is intended to help select a subset of target stars for TPF that have the best chance of harboring an Earth-like planet.

During FY 1999 a preliminary version of the Database was demonstrated to participants in a special Ames workshop on nearby stars (more below). Capabilities to help users examine data over the Web and define subset lists of interesting stars for further investigation were demonstrated. Substantial comments from the researchers attending the workshop were collected for further improvement of the Database and its user interfaces.

The Nearby Stars workshop was held over 3 days in June ‘99, organized and hosted by the NStars project scientists. The format involved a small number of invited speakers plus poster presentations. The invited talks addressed major topics in astrophysical research on nearby stars. The invited talks, posters, and notes from discussion sessions will be published as a NASA publication in 2000.

NStars project scientist Dana Backman addressed the SIRTF Science Working Group in March ‘99 about the NStars Project and its support for definition of SIRTF observing programs. Backman also gave a talk at the SOFIA Star Formation workshop in Santa Cruz in July ‘99 on possible SOFIA key projects investigating nearby stars.

Five undergraduate students (Avi Mandell, Aaron Burgman, Emma Roberts, Mike Connelley, and Pete Nothstein) worked as research assistants during summer and fall ‘99 on projects connected to NStars. Their projects included: a) comparison of techniques for determining ages of stars, b) surveys for variability of solar-type stars using a robotic telescope, and c) compilation of archived astronomical data to prepare for SIRTF observing programs. Software, database, and web page development for NStars involved part-time employment of Symtech personnel Sarah West, Eric Vacin, Mick Storm, and Peter Mariani. ❏

OBSERVATIONS OF EXTRASOLAR PLANETS

T. Castellano

In the last several years, more than 30 planets have been discovered orbiting other stars. All discoveries to date have been by the radial velocity method whereby extremely small variations in the speed of the star relative to Earth are used to infer the presence of an unseen orbiting companion. More than 20% of the planets discovered orbit their parent stars with periods of less than a week. For these short period orbits, 10% will be oriented such that the planet will periodically pass in front of the star as seen from Earth. An alternate method of detecting extrasolar planets employing high precision measurements of the stars brightness can confirm the existence of the planet and obtain its mass and radius. This technique was convincingly demonstrated when the first ever measurement of the dimming of a star (HD 209458) because of the passage of a orbiting planet occurred in late 1999. This ‘extrasolar planetary transit’ was discovered independently by two groups and widely reported in the news media.

Soon after the announcement, Ames conducted an archival search of the brightness data of the star HD 209458. The data, collected by the European Hipparcos satellite between 1989 and 1992, revealed a photometric dimming consistent with the observed radial velocity measurements and ground based transit observations. The long baseline in time between the Hipparcos measurements and the present allowed a very precise determination of the planet’s orbital period. These results will be published in the Astrophysical Journal Letters. The successful confirmation of an extrasolar planetary transit in the Hipparcos data, suggests that it may be possible to discover more extrasolar planets around sun-like stars using data from the Hipparcos satellite or NASA’s planned Full Sky Astrometric Explorer (FAME) satellite.

A novel method for obtaining high precision photometric measurements of bright stars using a spot filter and Charge Coupled Device Detectors on ground-based telescopes has been developed. A demonstration of the technique was performed on the sun-like star HD 187123 in the fall of 1999. No transit of an extrasolar planet was seen, although the required precision was achieved as shown in Figure 2. Additional observations were made of the stars bearing extrasolar planets HD 217107, 51 Pegasi, Upsilon Andromedae and Tau Bootes without result. ❑

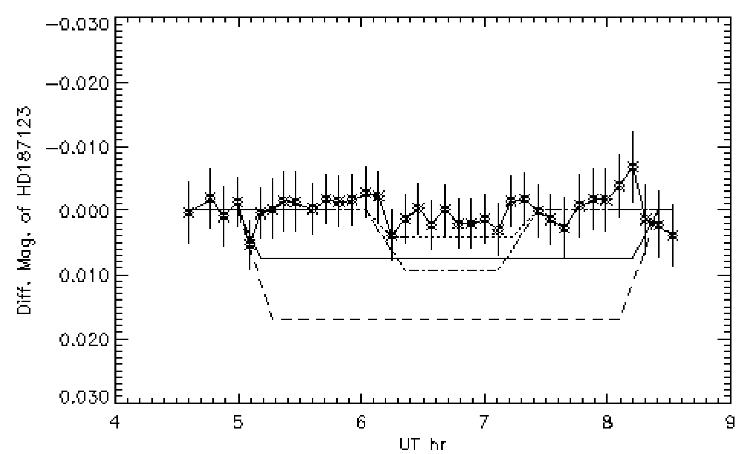

Figure 2: A sample of data for the star HD 187123 compared to a range of simulated possible transit signals produced by Jupiter like planets passing in front of a solar like star.

ORGANIC MATTER IN THE OUTER SOLAR SYSTEM

D.P. Cruikshank, T.L. Roush, Y.J. Pendleton, C. Dalle Ore, T.C. Owen, T.R. Geballe,
C. de Bergh, and B.N. Khare

Many solid bodies in the outer Solar System are covered with ices of various compositions, including water, carbon dioxide, methane, nitrogen, and other molecules that are solid at the low temperatures that prevail there. These ices have all been detected by remote sensing observations made with telescopes on Earth, or more recently, spacecraft in orbit (notably Galileo at Jupiter). The data also reveal other solid materials that could be minerals or complex carbon-bearing organic molecules. A study in progress using large ground-based telescopes to acquire infrared spectroscopic data, and laboratory results on the optical properties of complex organic matter, seeks to identify the non-icy materials on several satellites of Saturn, Uranus, and Neptune. The work on the satellites of Saturn is in part preparatory to the Cassini spacecraft investigation of the Saturn system, which will begin in 2004 and extend for four years.

One of Saturn's satellites, Iapetus, exhibits a unique exposure of non-ice surface material that has very low reflectivity, causing the surface to appear entirely black at certain positions in its orbit around the planet. The infrared spectrum of this black surface of Iapetus has been extended into new wavelength regions in the current study, exploring a part of the spectrum that has not heretofore been seen.

In addition to other characteristics of the spectrum of Iapetus, a very strong absorption band at 3 micrometers wavelength is revealed clearly for the first time in the new study. Models of the spectrum using organic solid materials produced in realistic simulations in the laboratory give a strong indication that the black matter on half of Iapetus' surface is indeed organic in nature. The origin and mechanism for emplacement of the black material on the surface of this moon are unknown. The Cassini mission to Saturn will provide data that have a high probability of resolving these issues and further clarifying the apparently unique history of Iapetus.

Other moons of Saturn show similar, though less dramatic, evidence for the presence of macromolecular organic matter mixed with their surface ices, but the chemistry of the organic material appears to be different. The moons of Uranus, Neptune's moon Triton, and the planet Pluto all have black materials on their surfaces that are presumed to be organic in nature. The origins of this material are likely to be different from that on Iapetus, as well, underscoring the extraordinary variety of compositions and histories that the small bodies of the outer Solar System have undergone since their formation. The study in progress at Ames, with colleagues from many other institutions, seeks to explore the nature and origin of organic matter throughout the Solar System, and to explicate any astrobiological connections that emerge. ❏

AIRES - THE SOFIA FACILITY SPECTROMETER

E. Erickson, M. Haas, and S. Colgan

An Ames team was selected by peer review to build AIRES, the Airborne Infrared Echelle Spectrometer for SOFIA, the Stratospheric Observatory for Infrared Astronomy. The objective is to develop a facility class spectrometer for use by the international astronomical community. AIRES will be delivered to the Universities Space Research Association (USRA) NASA's prime contractor for SOFIA, who will operate facility instruments for scientists with approved observing programs.

SOFIA is a unique airborne astronomical observatory currently under development. A Boeing 747 will be equipped to carry a 2.7-meter telescope to be operated at altitudes up to 45,000 feet, allowing infrared astronomical observations that are impossible from the Earth. It is being developed jointly by NASA and DLR, the German Aerospace Center, and will be based at Ames with operations beginning in late 2002.

AIRES will operate at far-infrared wavelengths, roughly 30 to 400 times the wavelengths of visible light. This means it will be ideal for spectral imaging of gas-phase phenomena in the interstellar medium (ISM), the vast and varied volume of space between the stars. Measurements of far-infrared spectral lines with AIRES will probe the pressure density, luminosity, excitation, mass distribution, chemical composition, heating and cooling rates, and kinematics in the various gaseous components of the ISM. These lines offer invaluable and often unique diagnostics of conditions in such diverse places as star-forming regions, circumstellar shells, the Galactic Center, starbursts in galaxies, and the nuclei of active galaxies energized by accretion of material on massive black holes. AIRES will provide astronomers with new insights into these and other environments in the ISM. It will also be useful for studies of solar system phenomena such as planetary atmospheres and comets, and a variety of other astronomical problems.

AIRES development began in November 1998. The design incorporates the world's largest monolithic 'echelle' grating (see Figure 3), an optical element which will provide good spectral resolution at far

Figure 3: The ruled echelle grating. Two images of the optical engineer are seen reflected from the facets of the grooves that are at angles of 90 degrees from each other.

infrared wavelengths. Two dimensional infrared detector arrays will be used to simultaneously measure spectra in a number of locations on the sky, and to verify the location on the sky where the instrument is acquiring data. During the past year, a number of significant milestones have been reached, including: a) The optical design has been completed; b) The echelle grating has been fabricated; c) The detector data system has been fabricated and tested with the imaging array detector; d) The baseline project resource requirements have been re-defined and the management revised; and e) An external preliminary design review team, selected by USRA, approved the project for continued development. ❑

CONCEPTUAL STUDY OF NGST SCIENCE INSTRUMENTS

T. Greene and K. Ennico

The Next Generation Space Telescope (NGST) will be the successor of the Hubble Space Telescope and is scheduled for launch in the year 2008. NGST will make unprecedented discoveries in the realms of galaxy formation, cosmology, stellar populations, star formation, and planetary systems. NGST is currently in the conceptual design phase of development, and Ames has been involved in defining and studying the scientific instrumentation it will need to conduct its observations.

Along with scientists at the University of Arizona (Kimberly Ennico, Jill Bechtold, George Rieke, Marcia Rieke, Jim Burge, Roland Sharlot, and Rodger Thompson), and in partnership with Lockheed Martin (Larry Lesyna and the Advanced Technology Center staff), Ames has led and completed a conceptual study of the entire NGST scientific instrument complement. This was one of several international teams selected to study NGST science instruments. The Ames-led team conducted trade studies of specific instrument technologies and implementations, and developed a comprehensive integrated science instrument module (ISIM) concept.

The team found that the science drivers of NGST justify observations from visible (0.4 microns) to far-infrared (35 microns; about 50 times longer than visible to the human eye) wavelengths of light. Imaging capability is required throughout this wavelength range, while spectroscopic capability is required at all wavelengths greater than or equal to 1 micron. Several technologies are key to achieving these capabilities within the cost, schedule, and environmental requirements of the NGST mission. Visible and far-infrared detectors could be developed in time for NGST, and several detector cooling options – including pulse tubes and solid H_2 systems – are viable. The team also found that dispersive slit spectrographs are superior to imaging Fourier Transform spectrometers when complete spatial coverage is not required. Dispersive spectroscopy may be best accomplished with conventional slits or micro-shutter arrays instead of micro-mirror arrays due to the large background rejection (greater than a factor of 1000) required at near-to-far infrared wavelengths.

A complement of 7 instrument modules resulted from these scientific and technical considerations by the study team. Two wide-field cameras (each covering about 0.01 square degrees) would be located directly at the focus of the NGST telescope and would image visible to near-infrared wavelengths

(0.4 – 2.5 microns) in a few broad-band filters. A separate visible-light camera would cover a smaller field at the maximum resolution of the NGST telescope. The other four modules would cover near-to-far infrared wavelengths of light (1–34 microns) and would be capable of conducting either imaging or dispersive spectroscopic observations with modest fields and good spatial resolution. The capability of providing both imaging and spectroscopy with relatively simple optical designs is enabled by using transmissive dispersion elements (called 'grisms') for spectroscopy. The conceptual layout of one of these modules is shown in Figure 4.

Several technologies must be developed further in order to implement this design concept and to ensure the success of NGST. Increasing the size (number of picture elements) and reducing the noise of infrared detectors will have the greatest scientific impact at relatively modest cost. Ames is already leading this effort for NGST. Reliable closed-cycle cryogenic coolers must also be developed to cool these detectors to temperatures of 4-30 degrees Kelvin above absolute zero. This task will be eased by the fact that the NGST telescope will always be behind a sun shade and will cool down to approximately 40 degrees Kelvin. However, these and all other NGST systems must be very reliable since NGST will be located approximately a million miles from Earth, far beyond the reach of the Space Shuttle, and will not be serviceable by astronauts. ❑

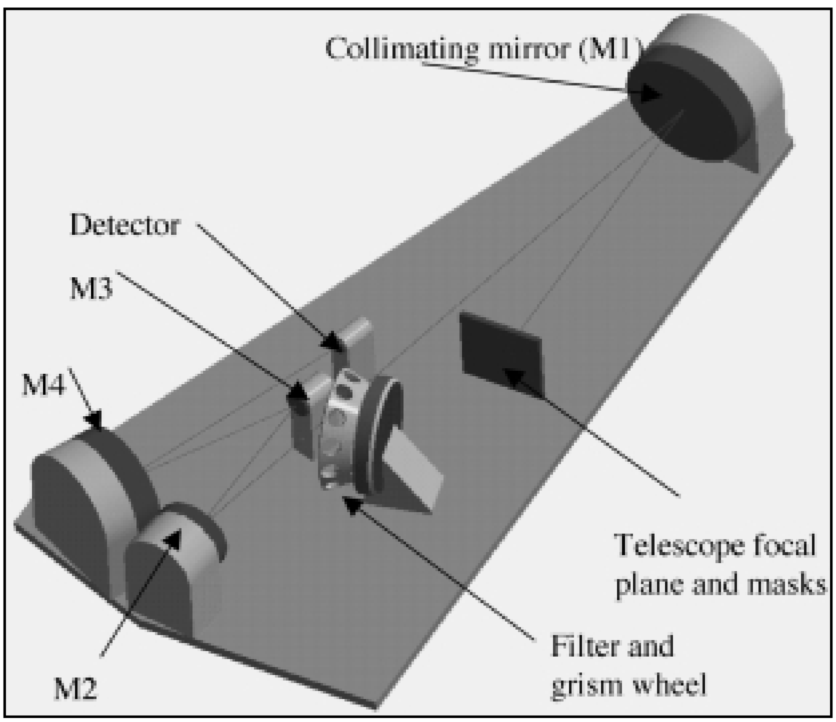

Figure 4: The optical layout of a single instrument module, that can operate as either a camera or spectrograph.

THE SOFIA TELESCOPE ASSEMBLY ALIGNMENT SIMULATOR

M.R. Haas, D.S. Black, J.C. Blair, P.A. Cardinale, N.N. Mai, M.S. Mak, J.A. Marmie, M.J. McIntyre, D.D. Squires, E. Stokely, K. Tsui, and B.C. Yount

NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) is scheduled to begin routine flight operations from Ames in early 2003. To facilitate installation and integration of science instruments with the observatory, a Telescope Assembly Alignment Simulator (TAAS) is being designed and built. Such a facility is required because of the high flight rate, frequent instrument change-outs, and limited access to the telescope cavity.

The TAAS will be an essential part of the Preflight Integration Facility in the SOFIA Science and Mission Operations Center. Before an instrument flies on SOFIA, it will first be mounted on the TAAS to: a) conform all mechanical and electrical interfaces; b) prepare the instrument for flight and assess its operational readiness; c) optically align the instrument with respect to the telescope; and d) measure the weight and moments of the instrument for use in balancing the telescope assembly. Because the TAAS has such a fundamental role in the preparation of science instruments for flight, a second unit will be permanently stationed in the Southern Hemisphere for use during deployments.

Figure 5 shows an advanced design for the main mechanical structure of the TAAS. Science instruments mount on the instrument-mounting flange and their associated electronics are housed in a rack attached to the counterweight plate. In order to provide an accurate mechanical reproduction of the telescope interface, the flange assembly and counterweight plate will be duplicates of those on SOFIA. The bearing unit assembly allows the science equipment to be rotated through the full range of elevation angles appropriate for SOFIA. The drive system powers the rotation and maintains an elevation angle, once selected. Three different infrared light sources have been designed to mount on the rear of the TAAS, for use in instrument alignments. A bore-sight camera assembly will be located in the horizontal tube of the TAAS; it will record focus and bore-sight information and facilitate its transfer to the telescope.

Patch panels will be mounted on the sides of the counterweight rack which are identical to those on the aircraft. Through these panels, the instrument will be connected to all essential services, such as vacuum and gas lines, electrical power, and computer communications to allow a full operational evaluation of the system. The communications will include connection to the observatory's computer simulator for protocol evaluation and testing of critical software interfaces.

The TAAS is mounted on load cells so that it can measure the weight and moments of instrument focal plane packages. These measurements will be used to infer the distribution of counterweights required to balance the SOFIA telescope about all three rotational axes for the given instrument configuration. With this information, the balancing procedure aboard the observatory should take less than an hour.

Preliminary design concepts have been developed for all TAAS subsystems, culminating in a successful preliminary design review in September 1999. Some critical subsystems have been prototyped in the laboratory, including the load cells and a special-purpose controller that modulates the signals from the alignment sources. ❑

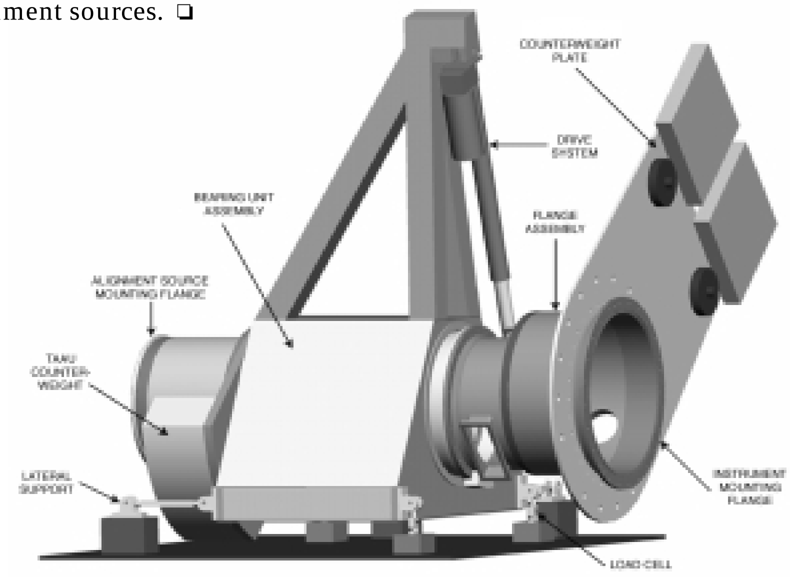

Figure 5: An Advanced Design for the Telescope Assembly Alignment Simulator.

CCD PHOTOMETRY TESTS FOR PLANET DETECTION

D. Koch, W. Borucki, J. Jenkins, L. Webster, and F. Witteborn

For the first time in history, we now know of more planets outside our solar system than in it. All of these extrasolar planets are about the size of Jupiter or larger. We have proposed the *Kepler Mission* to search for hundreds of Earth-size planets. The concept consists of monitoring 100,000 stars continuously for four years for planetary transits. An Earth-size transit of a solar-like star produces a relative change in brightness of $8x10^{-3}$ for a duration of a few to 16 hours depending on the planet's orbit and inclination. We have conducted a technology demonstration to show that a relative precision of better than $2x10^{-5}$ is achievable when all of the realistic noise sources are incorporated in a full-up end-to-end system. A commercially available back-illuminated CCD was used for the tests. The same device can be used in the proposed *Kepler Mission*.

The technology demonstration test facility incorporated the ability to control and measure the following effects on the noise performance of the end-to-end system: varying the CCD operating temperature, changing the focus, varying the photometric aperture, operating over a dynamic range of five stellar magnitudes, working in a crowded star field, reading out the CCD without a shutter, translating the image to several discrete locations on the CCD, operating with a field star five magnitudes brighter than the brightest target stars, operating with spacecraft jitter up to ten times the anticipated amplitude, and simulating the effects of cosmic rays and stellar variability.

The testbed source incorporates all of the characteristics of the real sky that are important to the measurements. It produces the same flux as real 9th to 14th magnitude stars, has the same spectral color as the Sun, has the same star density as the Cygnus region of the Milky Way down to stars as faint as 19th magnitude, has several 4th magnitude stars, and has the ability to produce Earth-size transits for selected stars. The camera simulates all of the functions to be performed by the space-borne photometer, namely, fast optics, a flight-type CCD, readout without a shutter, a high-speed readout of one mega-pixel per second and proto-flight data reduction and analysis software. Piezo-electric transducers are used to provide tip-tilt of the camera to reproduce the motion caused by spacecraft pointing jitter.

To fully demonstrate the concept, transits were created during the testing. Representative transits are shown in Figure 6 for 9th (left), 12th (middle) and 14th (right) magnitude stars. The transit depth is given in equivalent Earth-size and the error bars are the one-sigma noise for the data. ❑

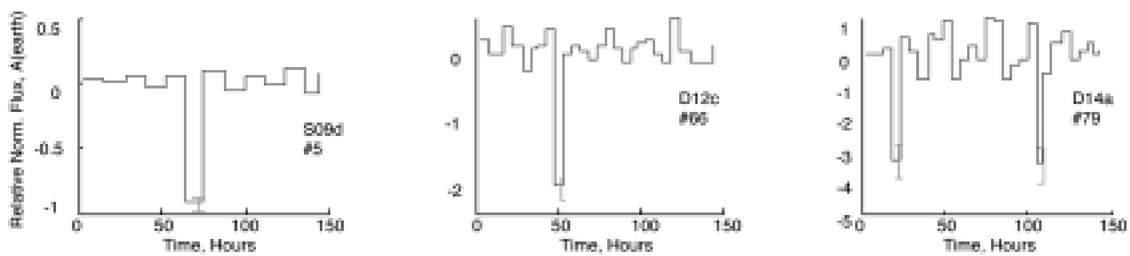

Figure 6: Simulated transits during the running of the long-duration test with all noise sources.

MINIMIZING INFRARED STRAYLIGHT ON SOFIA

A.W. Meyer, S.M. Smith, and C.T. Koerber

The Stratospheric Observatory for Infrared Astronomy (SOFIA) is now being designed and developed, with first light expected in fall, 2002. Flying at 41,000 feet or higher for six hours or more during 120 nights each year, SOFIA will be used for high-resolution observations of celestial objects in the infrared and submillimeter regions, spanning a factor of 1000 in wavelength. In many respects, building SOFIA is a greater challenge than an orbiting observatory would be, but advantages of economy and continuous access make it worthwhile. For work in the infrared, where everything at temperatures above absolute zero can be a source of background interference, the telescope and associated infrared sensors must be carefully designed and constructed to minimize such background. The far-infrared properties of the telescope's surfaces, surrounding cavity walls, and surfaces within focal-plane instruments can be significant contributors to background noise. Infrared radiation from sources well off-axis, such as the Earth, Moon, or aircraft engines may be multiply scattered by dust on the optics, the cavity walls and/or surface facets of a complex telescope structure. This report briefly describes recent efforts at NASA Ames to evaluate some of the infrared properties of the SOFIA telescope surfaces and some of the surface treatments that may be used in focal-plane infrared sensors.

In support of progress in the design and development of the SOFIA telescope, the Non-Specular

Reflectometer (NSR) at NASA Ames was re-activated and upgraded. This enabled the NSR to be use to measure infrared reflectance properties for samples of planned SOFIA telescope system structural materials and associated surface treatments. Measurements of specular reflectance and of Bi-directional Reflectance Distribution Functions (BRDFs) were made at wavelengths from 2.2micr ons to 640micr ons, at two angles of incidence, and at scattering angles as far as 85 degrees from normal. Samples of planned telescope system materials included carbon fiber reinforced plastic (CFRP), insulating foams, and Nomex fabric. Samples of candidate surface treatments for focal-plane instruments included two commercial surface treatments, and several samples prepared at Ames with black paints and other components. The commercial surface treatments investigated were ‘Optoblack,’ a paint-like surface treatment from Labsphere, Inc. (North Sutton, New Hampshire), and ‘Vel-Black,’ a carbon fiber applique from Energy Science Laboratories, Inc. (San Diego, California). In general, the samples of telescope structural materials appear to have acceptable far-infrared reflectance and scattering properties, even compared to surface treatments expressly developed to minimize such effects. Figure 7 shows specular reflectance results for the telescope samples, compared to infrared-optimized black paints. The commercial surface treatments appear to have excellent characteristics for use in the far-infrared. Samples prepared at Ames performed well when silicon carbide grit was mixed in. These Ames-prepared samples approached but did not equal the performance of more carefully developed infrared black paints such as Ames 24E2 and Ball Infrared Black (BIRB).

These empirical results can now be incorporated into a software model of the SOFIA telescope, which would provide predictions of likely infrared background noise levels. However, it appears already possible to say from the results of the above work, that the surfaces evaluated will probably not contribute significant infrared stray light. ❑

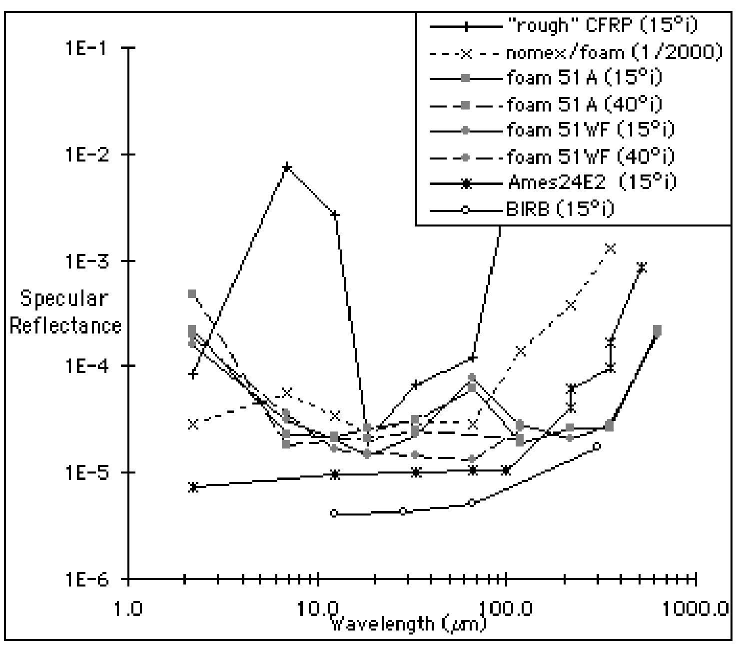

Figure 7: An example of surface treatment samples measured by the NASA Ames Non-Specular Reflectometer. Infrared reflectance spectra for samples of Rohacell white foam, roughened CFRP, Nomex over melamine foam, and for comparison previously published data for the black paints Ames 24E2 and BIRB.

THE SOFIA WATER VAPOR MONITOR

T.L. Roellig, R. Cooper, A. Glukhaya, M. Rennick, and B. Shiroyama

The Stratospheric Observatory for Infrared Astronomy (SOFIA), a 3-meter class telescope mounted in a Boeing 747 aircraft, is being developed for NASA by a consortium consisting of the University Space Research Association, Raytheon E-Systems, and United Airlines. This new facility will be a replacement for the retired Kuiper Airborne Observatory that used to fly out of Moffett Field. As part of this development, NASA Ames Research Center is providing an instrument that will measure the integrated amount of water vapor seen along the telescope line-of-sight. Since the presence of water vapor strongly affects the astronomical infrared signals detected, such a water vapor monitor is critical for proper calibration of the observed emission. The design of the water vapor monitor is now complete and engineering model units (EMUs) have been constructed for all of the important sub-assemblies.

The SOFIA water vapor monitor measures the water vapor content of the atmosphere integrated along the line-of-sight at a 40°-elevation angle by making radiometric measurements of the center and wings of the 183.3 GHz rotational line of water. These measurements are then converted to the integrated water vapor along the telescope line-of-sight. The monitor hardware consists of three physically distinct sub-systems:

1) The Radiometer Head Assembly, which contains an antenna that views the sky, a calibrated reference target, a radio-frequency (RF) switch, a mixer, a local oscillator, and an intermediate-frequency (IF) amplifier. All of these components are mounted together and are attached to the inner surface of the aircraft fuselage, so that the antenna can observe the sky through a microwave-transparent window. The radiometer and antenna were ordered from a commercial vendor and were modified at Ames to include an internal reference calibrator. Laboratory tests of this sub-assembly have indicated a signal-to-noise performance over a factor of two better than required.

2) The IF Converter Box Assembly, which consist of IF filters, IF power splitters, RF amplifiers, RF power meters, analog amplifiers, A / D converters, and an RS-232 serial interface driver. These electronics are mounted in a cabinet just under the radiometer head and are connected to both the radiometer head and the WVM CPU. Engineering model units for all the important components in this sub-assembly, including the entire RF signal chain, the RF detectors, and the low-noise power supplies have been constructed and tested in the lab. All easily meet their allocated performance requirements.

3) A host CPU, that converts the radiometer measurements to measured microns of precipitable water and communicates with the rest of the SOFIA mission and communications control system. A non-flight version of this computer has been procured for development and laboratory testing and the software architecture has been defined. Coding of prototype software has started and communications between the host CPU and the IF Converter Box Assembly have been demonstrated. ❑

THE INTERSTELLAR PRODUCTION OF BIOLOGICALLY IMPORTANT ORGANICS

S.A. Sandford, M.P. Bernstein, J. Dworkin, and L.J. Allamandola

One of the primary tasks of the Astrochemistry Laboratory at NASA's Ames Research Center is to use laboratory simulations to study the chemical processes that occur in dense interstellar clouds. Since new stars are formed in these clouds, their materials may be responsible for the delivery of organics to new habitable planets and may play important roles in the origin of life. These clouds are extremely cold (T <50 degrees Kelvin) and most of the volatiles in these clouds are condensed onto dust grains as thin ice mantles. These ices are exposed to cosmic rays and ultraviolet (UV) photons that break chemical bonds and result in the production of complex molecules when the ices are warmed (as they would be when incorporated into a star-forming region). Using cryo-vacuum systems and UV lamps, we simulate the conditions of these clouds and study the resulting chemistry. Some of the areas of progress made in 1999 are described below. Figure 8 shows some of the types of molecules that may be formed in the interstellar medium. Our laboratory simulations have already confirmed that many of these compounds are made under these conditions.

Polycyclic aromatic hydrocarbons (PAHs) are common in carbonaceous chondrites and interplanetary dust particles (IDPs), are abundant in space, and have been detected in interstellar ices. We have shown that PAHs that are UV processed in H_2O ices undergo both oxidation and reduction reactions. The resulting species include aromatic ketones, alcohols, ethers, and H_n-PAHs (partially reduced PAHs). In addition, isotopic studies show that this process can enrich PAHs in deuterium and may explain the D-enrichments seen in aromatics in meteorites. Our most recent studies on the UV processing of the PAH naphthalene in H_2O ice show that various naphthols and 1,4 -naphthaquinone are formed. Since naphthaquinones are common in living systems and perform fundamental roles in biochemistry (they are involved in electron transport), the extraterrestrial delivery of these compounds to the early Earth may be responsible for their presence in biochemistry.

We have continued our studies of the complex organics produced when 10 K interstellar ice analogs are UV irradiated. The residues remaining after the ices are warmed have been analyzed by HPLC and by laser desorption mass spectrometry (in collaboration with Prof. Richard Zare and colleagues at Stanford University). This material contains a rich mixture of compounds with mass spectral profiles resembling those found in IDPs. Surface tension measurements (made in collaboration with Prof. David Deamer of UC Santa Cruz) show that an amphiphilic component is also present. When our residues are dispersed in aqueous media, the organic material self-organizes into 10-40 micron diameter droplets that fluoresce at 300-450 nanometer under UV excitation. These droplets have morphologies that are strikingly similar to those produced by extracts of the Murchison meteorite. The amphiphilic nature of these materials is responsible for the molecular self-assembly and these compounds could have played a role in the formation of early membranous boundary structures required for the first forms of cellular life.

Together, these results suggest a link between organic material photochemically synthesized on the cold grains in dense, interstellar molecular clouds and compounds that may have contributed to the prebiotically important organic inventory of the primitive Earth. ❑

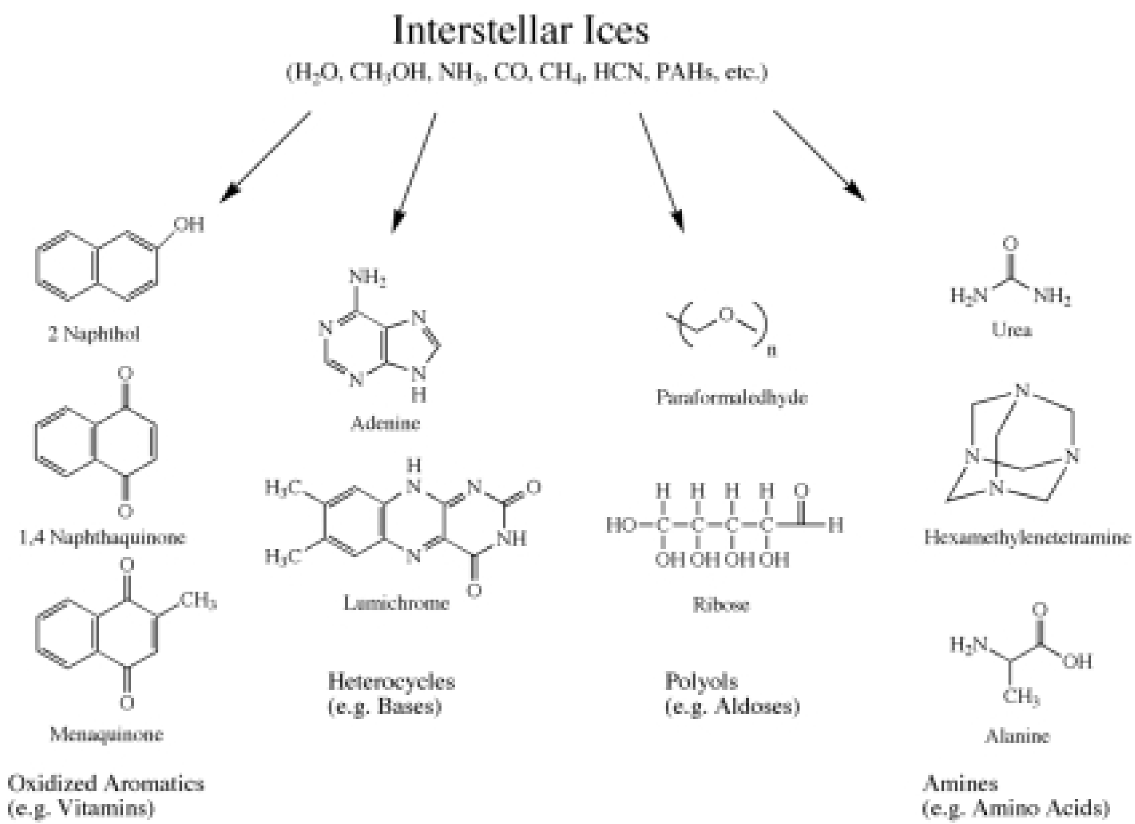

Figure 8: Some of the classes of compounds that may be produced in low temperature interstellar ices by UV photolysis. A number of these species have already been identified or tentatively identified in our interstellar simulations (2-naphthol, 1,4-naphthaquinone, paraformaldehyde, urea, hexamethylenetetramine, and alanine).